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TRANSPORT AND OXIDATION OF COMPARTMENT FIRE EXHAUST GASES IN AN ADJACENT CORRIDOR

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SUMMARY

The oxidation of underventilated compartment fire exhaust gases during their transport down a corridor adjacent to the compartment was experimentally investigated. External burning from a compartment has been reported to decrease the toxic exhaust gas levels downstream of the compartment. The focus of the investigation was to identify the phenomena controlling the oxidation of the combustion gases external of the compartment as they traveled down a corridor during external burning. Variables in the research included the fire size, the hallway inlet and exit soffit heights, and the vent area from which the exhaust gases exit the compartment. Through gas sampling both in the hallway and in the exhaust duct downstream of the hallway, the oxidation of carbon monoxide (CO) and total unburned hydrocarbons (UHC) was studied. The concentrations of CO and UHC were reduced from the entrance to the exit of the hallway by 65 percent and 98 percent, respectively, with no soffit at either end of the hallway. The addition of a 20 cm soffit at the hallway entrance dramatically improved the oxidation and dilution of CO and UHC, resulting in a reduction of 80 percent and 94 percent in CO and UHC concentrations; respectively, from the entrance to the exit of the hallway. A soffit at the hallway exit was found to inhibit the species oxidation and resulted in only a 51 percent and 94 percent reduction in CO and UHC concentrations, respectively, from the exit to the entrance of the hallway. Descriptions of the types of external burning which occurred for different soffit geometries are given and then related to how it affected the oxidation of the exhaust gases within the hallway. The global equivalence ratio (GER) in the compartment could not predict the post-hallway species yields, so correlations were developed to predict the CO and UHC yields downstream of the hallway using dimensionless groups derived from dimensional analysis.

INTRODUCTION

Exhaust gas inhalation is responsible for approximately two-thirds of the deaths in building fires[1,2]. Previous studies have indicated that CO is the most significant toxic exhaust gas for a wide range of fuels[3,4]. Due to its significance, CO has become a major topic of investigation in compartment fires. Concentrations of CO inside an underventilated burning compartment have been measured up to 6.4 percent-wet in a non-flammable compartment[5] and up to 14 percent-dry in a compartment with a wood lined ceiling[6].

Many fatalities in building fires occur in enclosed locations remote from the burning compartment[7]. A major component of these exhaust gases which are transported throughout the building is the odorless and colorless gas, carbon monoxide[3]. Few studies have investigated the transport of exhaust gases through a building. Hinkley *et.al.*[8] investigated the spread of flames by using a burner at a closed

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end of a corridor which impinged upon the ceiling, causing a ceiling jet to be formed along the hallway. The radiation heat transfer from the ceiling-jet to the floor and the air entrainment into the ceiling-jet were correlated to the flame length. Morikawa *et.al.*[4] and Fardell *et.al.*[3] studied the chemical composition of the environment at locations remote from a burning room. None of these studies, however, investigated the evolution of the exhaust gas composition as it was transported to locations remote from the burning compartment. The use of the global equivalence ratio to predict species yields inside a two-layer fire environment has been demonstrated through the hood experiments performed by Beyler[9], Toner *et.al.*[10] and Morehart *et.al.*[10]. The plume equivalence ratio,

$$\phi_p = \frac{\dot{m}_{fuel}/\dot{m}_{air}}{\left(\dot{m}_{fuel}/\dot{m}_{air}\right)_{st}} \qquad (1)$$

is defined as the ratio of the fuel vaporization rate and the air entrainment rate normalized by the stochiometric fuel to air ratio and is equivalent to the upper-layer equivalence ratio, also known as the global equivalence ratio, during the steady-state time of the fire. Gottuk[12], Tewarson[13] and Pitts[14] applied the global equivalence ratio concept to compartment fires. The global equivalence ratio will be referred to as simply the equivalence ratio for the remainder of the paper. Studies have indicated that a phenomena termed sustained external burning (the oxidation of fuel rich gases as they exhaust from a burning compartment and mix with ambient air) significantly reduces CO levels downstream of the compartment when the exhaust gases are vented to the open atmosphere[15]. During the steady-state of these underventilated compartment fire experiments, Gottuk *et.al.*[15] were able to correlate the CO yield downstream to the equivalence ratio.

This paper presents the results of a detailed investigation of the transport and oxidation of exhaust gases which spill into a hallway adjacent to the burning compartment. The focus of this study was to determine the phenomena which control the oxidation of the exhaust gases (CO and total unburned hydrocarbons [UHC]) during sustained external burning in the corridor. The key variables in the study were the equivalence ratio and the fluid dynamics in the corridor. For different equivalence ratios and particular fluid dynamic situations, the variation in the concentrations of the upper layer gases with the distance from the ceiling and the distance along the length of the hallway were investigated. Species yields were determined downstream of the corridor and compared to those yields seen in the compartment experiments performed by Gottuk[15]. Correlations were developed to predict the CO and UHC yields within the exhaust gases downstream of the hallway.

Experimental Apparatus and Procedure

A schematic of the experimental apparatus is shown in Figure 1. The inside of the compartment structure is split into two regions, the fire compartment and the plenum. The 1.52 m wide, 1.22 m deep, 1.20 m high fire compartment is located above the 1.52 m wide, 1.22 m deep, 0.37 m high plenum. The fire compartment is lined with 2.54 cm thick Fire Master, UL rated, fire insulation board. During a fire inside the fire compartment, the air is naturally drawn from the atmosphere into the plenum from the back of the structure through a 0.30 m diameter, 1.83 m long circular duct. The air in the plenum enters the fire compartment through two 1.22 m wide, 0.13 m high thermally shielded openings. To allow the combustion gases to build up in the upper-layer of the compartment, there is a 20 cm high soffit inside of the compartment. The upper-layer of combustion gases within the compartment becomes thicker than the soffit height, resulting in the spilling of the gases into the hallway through an adjustable size, window style exhaust vent. The vent can be adjusted to a size as large as 50 cm wide by 75 cm high (3750 cm^2); however, for the experiments reported here the vent sizes used were 25 cm by 16 cm (400 cm^2), 50 cm by 16 cm (800 cm^2), and 50 cm by 25 cm (1200 cm^2). The top of the vent opening is always located at the bottom of the soffit inside the compartment. The fire size within the compartment is varied

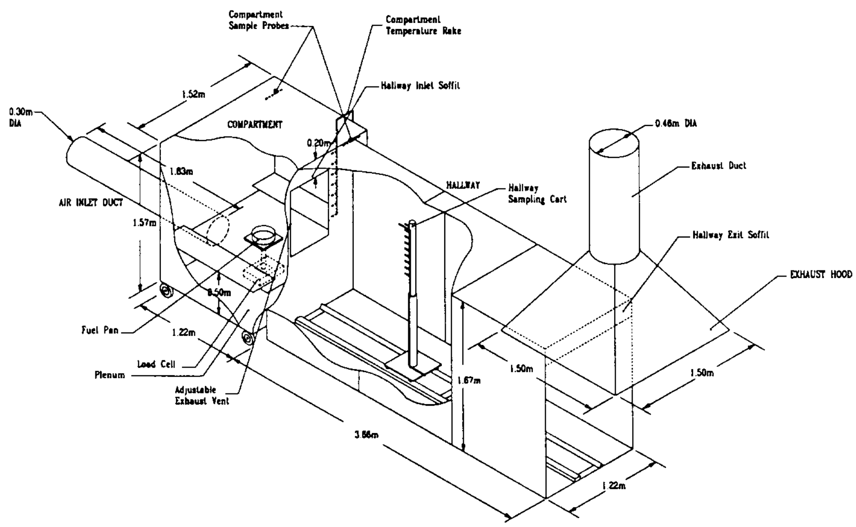

Figure 1. The compartment fire facility at Virginia Polytechnic Institute and State University.

by using either a 20 cm or a 23 cm diameter fuel pan, the exhaust vent size, and a different initial compartment temperature.

The combustion gases exit the compartment through the exhaust vent and enter a 1.22 m wide, 3.66 m long hallway. The height of the hallway is adjusted to the desired hallway inlet soffit height. The hallway is 1.47 m high with no inlet soffit and is 1.67 m high with a 20 cm inlet soffit. The hallway ceiling is lined with 2.54 cm thick Fire Master, UL rated, fire insulation board, while the walls consist of gypsum board lined with 1.5 mm thick Fiberfax ceramic fireproof paper. The fire gases travel down the hallway and are collected by a 1.5 m by 1.5 m fume hood which is connected to a 0.46 m diameter exhaust duct. The volumetric flow rate within the exhaust duct was determined by measuring the pressure drop across an orifice plate inside the exhaust duct[16].

According to Equation 1, the mass flow rate of the air entrained into the compartment and the fuel vaporization rate must be determined to calculate the equivalence ratio. By measuring the velocity of the air in the air inlet duct with a Kurz Model 415, hot film velocity probe calibrated for a velocity of 0-2 m/s and the temperature of the air in the duct using a type K thermocouple, the mass flow of air into the compartment was determined. The fuel pan rests on a platform that sits on a 15 kg A&D load cell (1 gram resolution) located in the plenum. The load cell was used to measure the fuel vaporization rate. From the known stochiometric ratio of the fuel, liquid hexane, the equivalence ratio was determined.

The temperature profiles of the combustion gases were measured in one corner of the compartment and at the sample cart location within the hallway (see Figure 1). The aspirated thermocouple rake within the compartment consists of eight type K (chromel alumel) thermocouples which are vertically spaced 10 cm apart. The rake, made of 0.635 cm stainless steel tubing, is 10 cm away from both walls with the top thermocouple 10 cm below the ceiling. The thermocouple rake in the hallway is part of a sampling cart and consists of nine type K thermocouples vertically spaced 5.1 cm apart. The location of the rake can be varied in all three directions.

For the tests reported herein, gases were sampled in the hallway and in the exhaust duct. Gas sampling in the hallway was done at various locations within the upper-layer using the sampling cart and is termed in-hallway sampling. The evolution of the exhaust gases down the corridor was determined by locating the sampling cart at different positions along the length of the hallway, termed an axial-profile. The sample probe for the axial-profile was always 5.1 cm below the ceiling and at an equal distance from each side wall. This location was chosen so the unburned upper layer gases could be monitored as they were being transported down the hallway and potentially into the exhaust duct. The gases were also sampled far enough below the ceiling to be able to ignore the cooling effects of the ceiling. To determine the distribution of the exhaust gases within the upper-layer, the sampling probe distance from the ceiling was varied, referred to as a vertical-profile. As in the axial-profiles, the sample probe for the vertical profiles was also in the middle of the hallway. The distance at which the gases were sampled below the ceiling was variable depending upon the expected upper layer depth. To determine how well the exhaust gases oxidized within the hallway, it was necessary to sample the exhaust gases downstream of the hallway within the fume hood exhaust duct, termed downstream sampling.

All sample lines leading to the gas analyzers (except for the high temperature, flexible Teflon tubing connecting the sampling cart probe with the heated stainless steel sample line at the end of the hallway) are heated to prevent the gases from condensing. Once the gases were sampled and drawn into the data acquisition room, they were split into two streams. Half of the gases remained wet and were directed towards a Gow-Mac flame ionization detector (FID) to measure the UHC, calibrated to measure as ethylene (C_2H_4). The other half of the sample was run through a water trap and then branched off into three lines. One line led to a Siemens paramagnetic Oxymat 5E analyzer to measure the dry concentration of oxygen (O_2), while the other two lines led to two separate Beckman NDIR model 880 analyzers to measure the dry concentrations of CO and carbon dioxide (CO_2).

The location and position of the sampling was not varied during a test, so each point on the graphs to be shown was the result of a single experiment. All of the temperature data, species data, and flow rate data were acquired every 0.033 seconds (a 188 Hz sampling frequency) using a computer. The data acquisition program averaged two seconds of sampled data to generate a single raw data point. The series of raw data points was reduced to a single point by averaging over a window of raw data points during sustained external burning within the hallway. The window was centered around the maximum value of CO during the external burning time. Twenty seconds of raw data was averaged when sampling in the hallway and in the compartment, while thirty seconds of raw data was averaged in the exhaust duct. Since the data taken when sampling downstream of the hallway was diluted, the variations in this data were smaller. This resulted in a longer time span over which the data could be averaged. Because conditions in the hallway and in the compartment changed more rapidly than those in the exhaust duct, shorter averaging spans were necessary during hallway and compartment sampling to accurately analyze the "quasi"-steady state period. Each experiment was recorded using a video camera to provide a permanent visual record of the development and burning of the exhaust gases within the hallway.

Results and Discussion

To investigate the oxidation and transport of the exhaust gases, sampling was first performed downstream of the hallway to determine the overall degree of oxidation of the gases. The evolution of the exhaust gas oxidation and transport within the hallway was then studied by sampling in the axial and vertical directions within the upper-layer present in the corridor.

In the experiments, the effects of altering the fluid mechanics within the hallway and the equivalence ratio within the compartment on the evolution of the compartment exhaust gases were investigated. The fluid mechanics within the corridor were varied by changing the soffit geometries at the entrance and exit of the hallway, the exhaust vent area and the fire size. The four soffit combinations used in the experiments were:

- *Case A:* no soffit at both the inlet and the exit (0/0),
- *Case B:* no soffit at the inlet and a 20 cm soffit at the exit (0/20),
- *Case C:* a 20 cm soffit at the inlet and no soffit at the exit (20/0) and

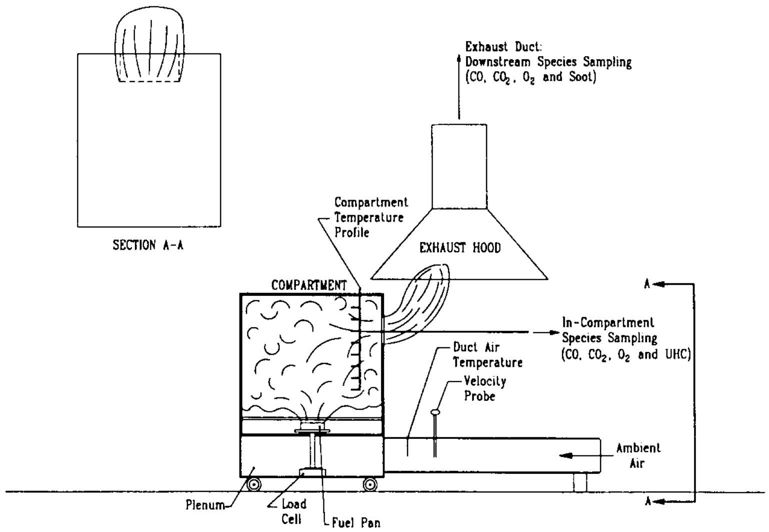

Figure 2. A schematic of the free-jet experiments performed by Gottuk[12].

- *Case D*: a 20 cm soffit at the inlet and a 20 cm soffit at the exit (20/20).

Different equivalence ratios within the compartment were achieved by varying the initial compartment temperature, the exhaust vent area and the fire size. Increasing the initial temperature, increasing the fire size and decreasing the vent area led to an increase in the equivalence ratio.

Post-Hallway Results

The sampling of gases downstream of the corridor was performed first to gauge the degree of oxidation of the exhaust gases within the hallway. The downstream species yields

$$Y_{E,i} = \frac{\dot{m}_i}{\dot{m}_{fuel}} \tag{2}$$

where;

$$\dot{m}_i = X_{E,i}(\dot{n}_{exh})MW_i \tag{3}$$

were plotted against the equivalence ratio and were compared to the results of the experiments performed by Gottuk[12]. The oxidation efficiency of a species

$$\eta_{oxid} = \left(1 - \frac{Y_{E,i}}{Y_{C,i}}\right)100 \quad [\%] \tag{4}$$

within the hallway was used to compare how effectively the in-compartment species yields were reduced by external burning. The average in-compartment yields determined by Gottuk[12] were used for $Y_{C,i}$ in this calculation. Note that a low downstream species yield corresponds to a high oxidation efficiency.

Gottuk[12] performed experiments where exhaust gases were permitted to spill out of the compartment directly into the open atmosphere underneath a fume hood. When the equivalence ratio was greater than 1.7, the gases exiting the compartment ignited forming a free, buoyant burning jet at the compartment exhaust vent (termed a free-jet), as seen in Figure 2. A thermally unstable environment and a high interfacial area between the jet and the ambient air are the two major reasons why this configuration resulted in the most efficient mixing between the air and the exhaust gases. Due to this efficient mixing, the species yields of UHC and CO downstream of the compartment were at a minimum in the free-jet experiments compared to the yields of UHC and CO obtained downstream of a hallway connected to the compartment. Gottuk[15] reported that for sufficiently underventilated fires, an equivalence ratio greater than 1.7, the average in-compartment yield for CO was 0.22 while the yields downstream of the compartment ranged from 0.022 to 0.055. The UHC yields within the compartment averaged 0.33 for these underventilated fires but no downstream UHC measurements were performed by Gottuk[12].

The yields of CO and UHC for the (0/0) soffit

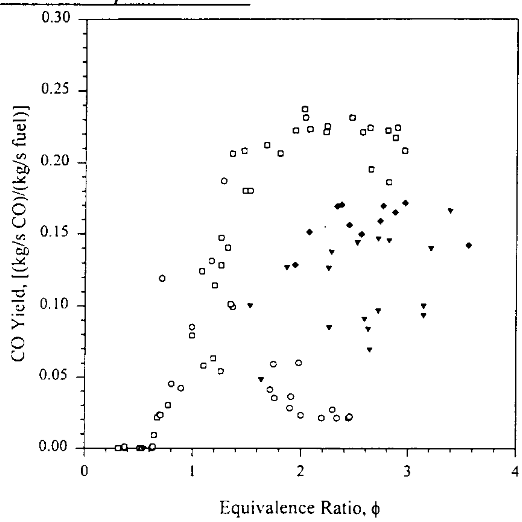

Figure 3a. The CO yield downstream of a hallway with soffit geometries of (0/0) and (0/20) plotted against the equivalence ratio. The open symbols represent results from the study performed by Gottuk[12]. The graph notation is as follows: □-In-compartment, O-downstream of free-jet, ▼-(0/0) soffit geometry and ◆-(0/20) soffit geometry.

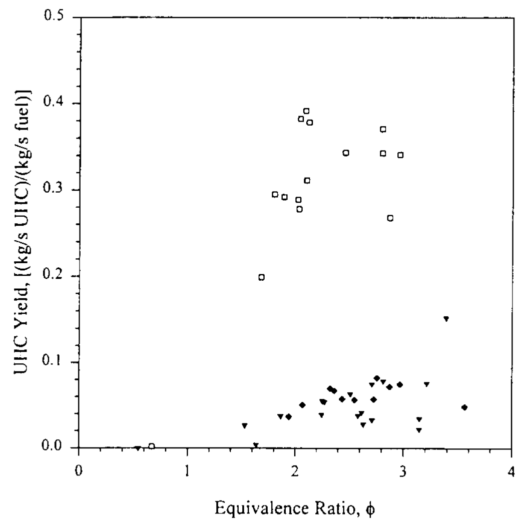

Figure 3b. The UHC yield downstream of a hallway with soffit geometries of (0/0) and (0/20) plotted against the equivalence ratio. The open symbols represent results from the study performed by Gottuk[12]. The graph notation is as follows: □-In-compartment, ▼-0/0) soffit geometry and ◆-(0/20) soffit geometry.

combination are plotted against the equivalence ratio along with the results of Gottuk[12] in Figures 3a and 3b, respectively. Downstream of the corridor, the CO yields ranged from 0.070 to 0.100 while the UHC yields were 0.022 to 0.055. From Table 1, it can be seen that the UHC were oxidized more efficiently within the hallway compared to CO. Also, the downstream CO yields were higher than those seen by Gottuk[15] in the free-jet experiments.

The yields of CO and UHC plotted against the equivalence ratio for the (0/20) soffit combination are also shown in Figures 3a and 3b, respectively. Downstream of the hallway, the CO yield levels for this soffit case varied between 0.128 and 0.171 while the yields for the UHC ranged from 0.037 to 0.082. The addition of the exit soffit inhibited the oxidation of the exhaust gases causing a reduction in the oxidation efficiency for both CO and UHC, see Table

Table 1. The oxidation efficiency ranges of CO and UHC within a hallway adjacent to an underventilated compartment fire. The global equivalence ratio in the experiments ranged from 1.6 to 3.5.

		Hallway Experiments for Different Soffit Geometries			
Species	Free-Jet Experiments, (Gottuk[12])	0 cm Inlet 0 cm Exit (0/0)	0 cm Inlet 20 cm Exit (0/20)	20 cm Inlet 0 cm Exit (20/0)	20 cm Inlet 20 cm Exit (20/20)
CO	75-90%	54-68%	22-42%	45-89%	39-91%
UHC	N/A	83-93%	75-89%	88-97%	86%-98%

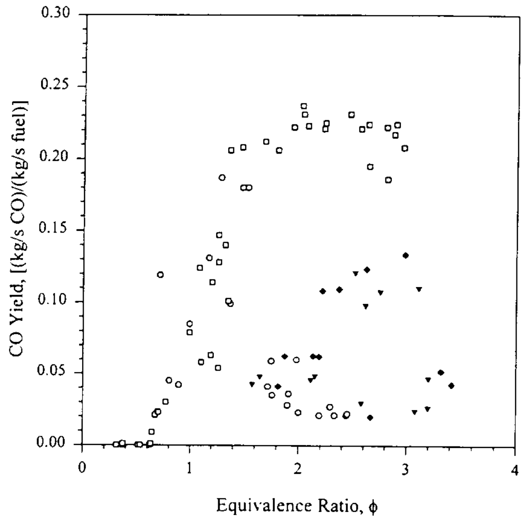

Figure 4a. The CO yield downstream of a hallway with soffit geometries of (20/0) and (20/20) plotted against the equivalence ratio. The open symbols represent results from the study performed by Gottuk[12]. The graph notation is as follows: □-In-compartment, O-downstream of free-jet, ◆-(20/0) soffit geometry and ◆-(20/20) soffit geometry.

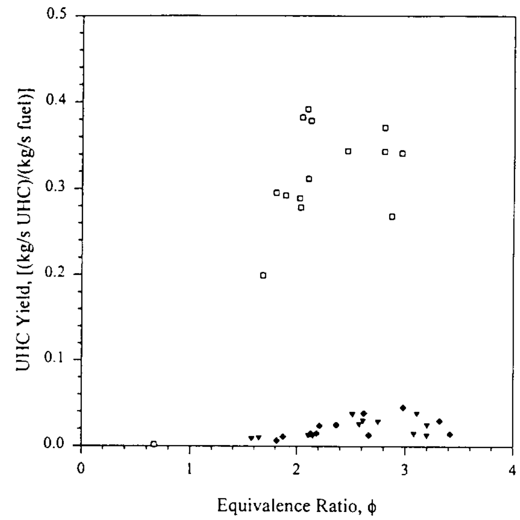

Figure 4b. The UHC yield downstream of a hallway with soffit geometries of (20/0) and (20/20) plotted against the equivalence ratio. The open symbols represent results from the study performed by Gottuk[12]. The graph notation is as follows: □-In-compartment, ▼-(20/0) soffit geometry and ◆-(20/20) soffit geometry.

1, compared to those levels seen in the (0/0) soffit geometry. The UHC were still oxidized more efficiently than the CO.

Shown in Figures 4a and 4b are the CO and UHC yields, respectively, for the (20/0) soffit combination plotted versus the equivalence ratio. Downstream of the corridor, the CO yields varied from 0.024 to 0.121 and the UHC yields ranged between 0.009 and 0.038. The addition of a 20 cm inlet soffit dramatically increased the oxidation efficiency of CO and mildly increased the oxidation of UHC, as can be seen in Table 1. The 20 cm inlet soffit allowed a buoyant plume to be formed at the entrance of the corridor compared to the ceiling-jet which was formed at the hallway entrance in the absence of an inlet soffit [(0/0) and (0/20) soffit geometries]. Alpert[17] and Hinkley *et.al.*[8] reported that a buoyant plume entrains air more efficiently than a ceiling-jet. Therefore, the presence of a buoyant plume at the hallway entrance led to an increase in the air entrainment at the entrance of the corridor and resulted in a more efficient oxidation of the exhaust gas.

The CO and UHC yields for the (20/20) soffit geometry are plotted against the equivalence ratio and are also shown in Figures 4a and 4b. In these experiments, the yields for CO varied from 0.020 to 0.134 and the UHC yield results ranged from 0.006 to 0.045. The effect that the addition of the 20 cm exit soffit with a 20 cm inlet soffit present has on the species oxidation was not as pronounced as that seen in the (0/0) and (0/20) cases, but the oxidation efficiencies still dropped slightly, see Table 1. Due to the efficient oxidation which occurred in the first half of the hallway, the species yields in some experiments were not affected by the addition of the exit soffit and the exhaust gases were oxidized as efficiently as seen in the (20/0) soffit combination. In experiments with larger size fires and a large exhaust vent area, the exit soffit slightly impeded the oxidation of the exhaust gases.

In-Hallway Results

In order to explain how and why the exit soffit impeded the oxidation of the exhaust gases and the inlet soffit enhanced the oxidation within the hallway, sampling of the upper-layer gases within the corridor was performed. Results of sampling in the hallway are presented according to the soffit geometries present in the corridor. Along with the data describing the axial and vertical variation in the concentrations of exhaust gases within the hallway, a description of the types of external burning which occurred within the hallway and its effects on the oxidation of CO and UHC is given.

The exhaust gas species have been normalized in the figures containing the axial and vertical species profiles of the hallway upper-layer. In the vertical-profiles, the CO and UHC species wet concentrations are normalized using the values closest to the ceiling while the CO_2 and O_2 species are normalized by values of 20 percent and 21 percent, respectively. The normalizing value for CO_2 is the maximum span gas value while the normalizing value for O_2 isapproximately the concentration of O_2 within the surrounding air. For the axial-profiles, the CO and UHC wet concentrations are normalized using the concentration of each species at the location closest to the compartment, while CO_2 and O_2 are normalized with the values of 20 percent and 10.5 percent, respectively. The normalizing value for O_2 is approximately half the concentration of O_2 within ambient air, since the region where the gases were sampled in the axial profiles had very low concentrations of O_2. The normalizing values appear in parentheses in all relevant figure captions.

Based on the chemical reactions which were occurring within the upper-layer of the hallway, the measured gas temperatures in *Case A.* and *Case B.* were unrealistically lower than expected and were corrected to account for the on-going chemistry.

Case A. 0 cm inlet and 0 cm exit hallway soffits (0/0)

With no soffit at the inlet and exit of the hallway, a confined ceiling-jet was formed along the length of the hallway, as seen in the graphical representation shown in Figure 5. As is noted by Hinkley *et.al.* [8], vortical structures were formed at the corners of the ceiling and the side walls. These vortical structures, however, did not separate into two different flames as they traveled down the hallway. Instead, these structures remained connected by a flame sheet as shown in the cross-sectional view A-A in Figure 5. These vortical structures eventually disappeared as the flame intensity diminished along the length of the hallway. With increasing fire size, the vortical structures were more well defined and persisted further down the hallway. The results presented for this soffit geometry are for fires burned in a 20 cm diameter fuel pan and for an exhaust vent area of 1200 cm^2 present at the hallway entrance.

Vertical-profiles were mapped at three axial locations (0.46 m, 1.83 m, and 3.20 m away from the compartment) along the hallway and are shown in Figures 6a, 6b and 6c. The average equivalence ratios for the experiments at each axial location was 1.92, 2.33 and 2.20, respectively, while the average fire size was 402 kW, 434 kW and 438 kW, respectively. Upon inspection of the profiles, three distinct regions of gases appeared to be present near the ceiling in the hallway. The region closest to the ceiling was a layer of fuel rich gases which

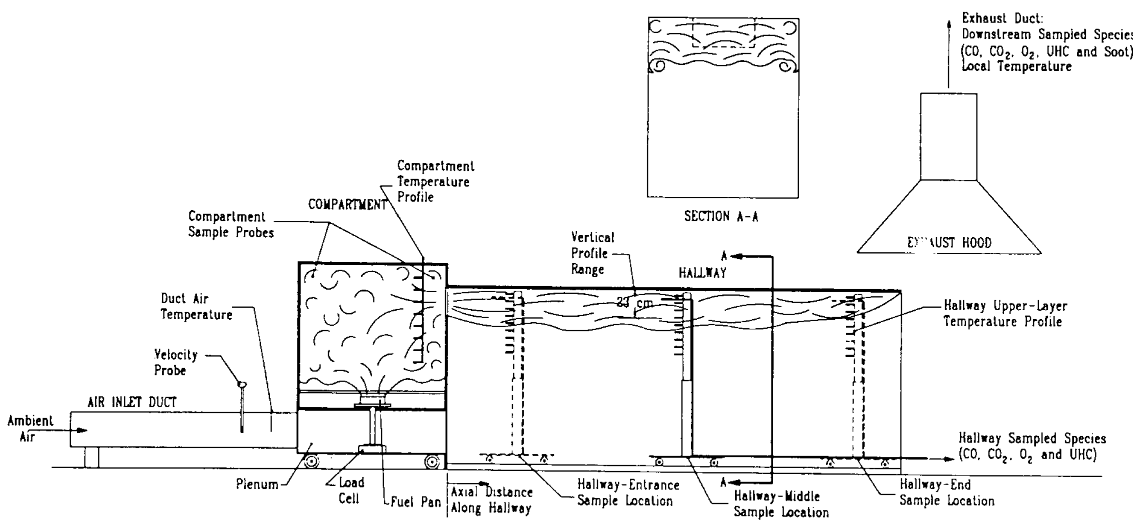

Figure 5. The ceiling-jet external burning which was present within a hallway having soffit geometries of (0/0) and (0/20).

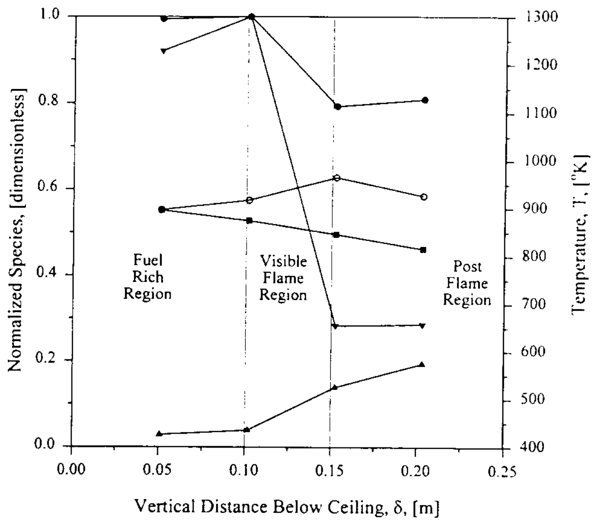

Figure 6a. The vertical-profile of the species concentrations within the upper-layer in a (0/0) soffit geometry hallway 0.46 m down the corridor from the compartment. The average equivalence ratio was 1.92 and the average fire size was 402 kW. The graph notation and normalizing values are as follows: ●-CO(0.87%), ▼-UHC(1.56%), ■-CO_2(20%) and ▲-O_2(21%) and O-Temperature.

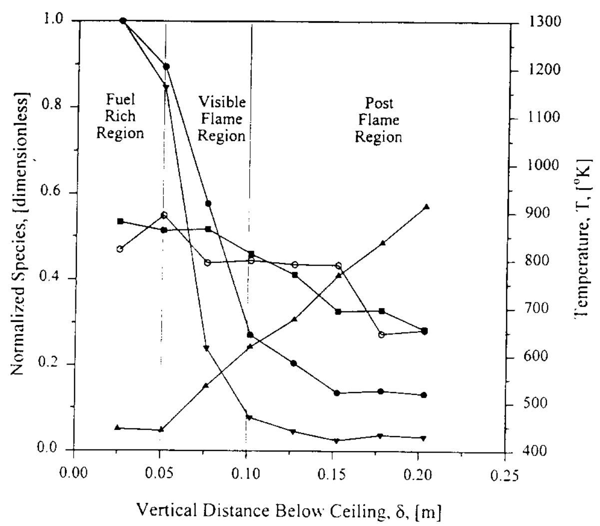

Figure 6b. The vertical-profile of the species concentrations within the upper-layer in a (0/0) soffit geometry hallway 1.83 m down the corridor from the compartment. The average equivalence ratio was 2.33 and the average fire size was 434 kW. The graph notation and normalizing values are as follows: ●-CO(0.87%), ▼-UHC(1.34%), ■-CO_2(20%), ▲-O_2(21%) and O-Temperature.

were being transported down the hallway and oxidized by the entrainment of air (the oxidation rate limiting process) into the upper-layer. The fuel rich region characteristically had the highest concentrations of CO and UHC and the lowest concentration of O_2. Underneath the fuel rich region was the visible flame region.

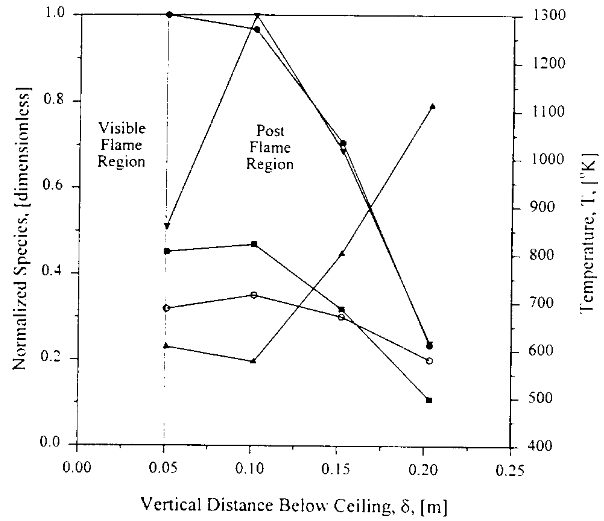

Figure 6c. The vertical-profile of the species concentrations within the upper-layer in a (0/0) soffit geometry hallway 3.20 m down the corridor from the compartment. The average equivalence ratio was 2.20 and the average fire size was 438 kW. The graph notation and normalizing values are as follows: ●-CO(0.39%), ▼-UHC(0.14%), ■-CO_2(20%), ▲-O_2(21%) and O-Temperature.

The position of visible flame region was estimated by the location of the highest gradient in the CO and UHC concentrations. The visible flame region usually included the highest temperature within the upper-layer. The third region was the post flame region which was apparent by a sudden reduction in the oxidation rate of CO and UHC along with a steady increase in O_2 concentration. The decrease in the concentration of the combustion gases with distance from the ceiling in this region was obviously caused by air dilution. The hallway upper layer thickness

$$\delta_{U\text{-}L} = \delta_{FRR} + \delta_{VFR} \quad (5)$$

consisted of the fuel rich region thickness, δ_{FRR} and the visible flame region thickness, δ_{VFR}. The thickness of the upper-layer along the length of the hallway was $\delta_{U\text{-}L}\approx$10-15 cm at 0.46 m, $\delta_{U\text{-}L}\approx$5-10 cm at 1.83 m and $\delta_{U\text{-}L}\approx$0-5 cm at 3.20 m away from the compartment. The thickness of the upper layer along the hallway varied with the fire size, the vent area and the hallway soffit geometry. As expected, the measured upper layer thickness in the hallway decreased as the gases were oxidized down the length of the hallway. This was visually seen to be the case in all the experiments in which a ceiling-jet was present in the hallway.

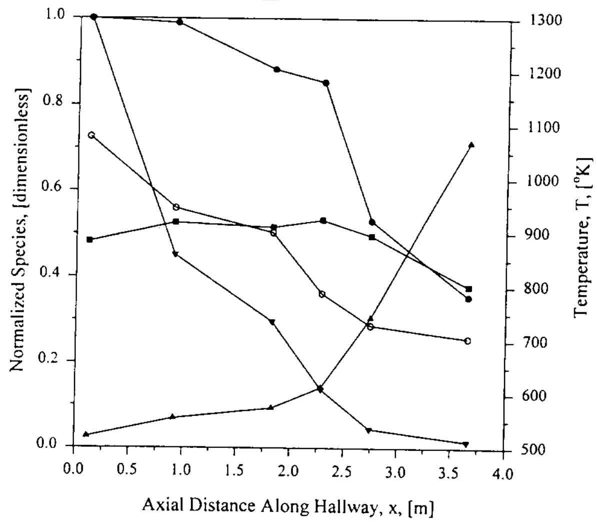

Figure 7. The axial-profile of the species concentrations within the upper-layer in a hallway having a soffit geometry of (0/0). The average equivalence ratio was 2.47 and the average fire size was 488 kW. The graph notation and normalizing values are as follows: ●-CO(0.88%), ▼-UHC(3.87%), ■-CO_2(20%), ▲-O_2(10.5%) and O-Temperature.

The variation in the exhaust gases along the length of the hallway is shown in Figure 7. The experiments used to create the profile had an average equivalence ratio of 2.22 and an average fire size of 433 kW. The flame length in the hallway was determined from the increase in O_2 levels, the dilution of CO_2 and, as noted from the kinetic modeling of Pitts[18] and Gottuk[12], the gas temperature in the 700 to 800°K range. This temperature range is similar to the flame extinction temperatures of 773°K reported for vertical buoyant flames. Using these criteria, the profile shown in Figure 7 indicates that the flame extinguished between 2.8 m and 3.6 m down the hallway and was verified to extend 3.0 m down the corridor using the visual record of the tests. Also consistent with modeling results was the faster reduction of UHC levels compared with CO. The oxidation reaction rate of the UHC at low temperatures, up to approximately 1100°K, is higher than that of CO resulting in the more rapid reduction of UHC compared to CO[19]. Furthermore, when the UHC were oxidized they formed CO, thus increasing the concentration of CO within the upper-layer. The oxidation rates of CO and UHC began to decrease ("freeze out") around 950°K which occurred approximately 2.25-2.75 m down the hallway[20]. Past this point, the entrained air was not used for the oxidation of CO and UHC, but instead acted as a diluent of the upper-layer gases. This is evident in Figure 7 by the decreasing levels of CO and UHC along with a decrease in the level of CO_2 and an increase in the O_2 concentration. The concentrations of CO and UHC at the hallway exit were reduced by 65 percent and 98 percent, respectively, of the hallway entrance concentrations.

Case B. 0 cm inlet and 20 cm exit hallway soffits (0/20)

As in the previous case, a confined ceiling-jet of fire was produced upon the ignition of the compartment exhaust gases within the hallway having a (0/20) soffit geometry. The graphical representation of this situation was similar to that seen in Figure 5 except the upper-layer thickness was greater. The vortical structures mentioned in the last section were also present in this case.

The vertical profile of the upper-layer gases 1.83 m down the hallway from the compartment is seen in Figure 8. The experiments used to generate the vertical-profile consisted of an 800 cm^2 exhaust vent area and a 20 cm diameter fuel pan pool fire inside the compartment.

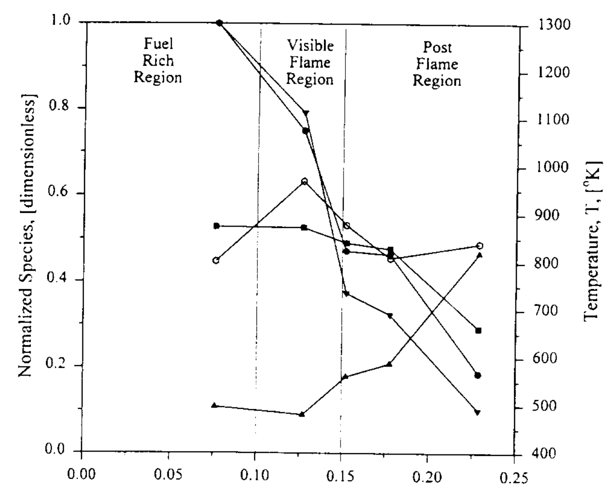

Figure 8. The vertical-profile of the species concentrations within the upper-layer in a hallway having a soffit geometry of (0/20). The average equivalence ratio was 2.81 and the average fire size was 445 kW. The graph notation and normalizing values are as follows: ●-CO(1.09%), ▼-UHC (1.04%), ■-CO_2(20%), ▲-O_2(21%) and O-Temperature.

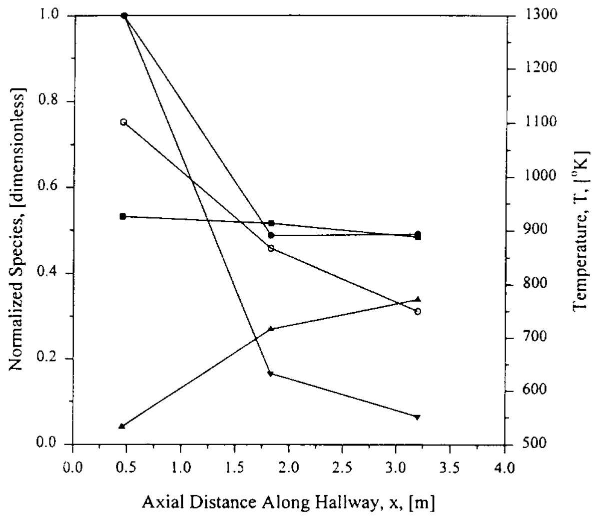

Figure 9. The axial-profile of the species concentrations within the upper-layer in a hallway having a soffit geometry of (0/20). The average equivalence ratio was 1.90 and the average fire size was 409 kW. The graph notation and normalizing values are as follows: ●-CO(0.87%), ▼-UHC (1.39%), ■-CO_2(20%), ▲-O_2(10.5%) and O-Temperature.

Based on the visual records and th.: downstream species yields, there was not a large variation in the behavior of the external burning with an 800 cm vent area compared to a 1200 cm vent area. The fires which made up the vertical-profile shown in Figure 8 had an average equivalence ratio of 2.81 and an average fire size of 445 kW. From Figure 8, the upper-layer thickness in the middle of the hallway was seen to increase to approximately 10-15 cm when an exit soffit was attached to the hallway. The upper-layer thickness was approximately the same for a 1200 cm^2 vent area based on the temperature profiles within the hallway and the visual record of the test.

The axial profile for the (0/20) soffit geometry is shown in Figure 9. A 1200 cm^2 exhaust vent area and a 20 cm diameter fuel pan were used in these experiments. The average equivalence ratio and the average fire size used to generate the axial-profile were 1.90 and 409 kW, respectively. Using Figure 9, the flame length was estimated to be approximately 3.2 m down the hallway, since the temperature here was close to the temperature where the flame is seen to extinguish. From the visual records of the fires, the flame was seen to extend approximately 3.2 m down the hallway. The UHC were seen to oxidize faster than the CO within the first part of the hallway. In the second part of the hallway, the reactions began to "freeze out" and the gases began to be diluted by the entrained air. This was evident by the low temperatures, the rising O_2 levels and the falling CO_2 levels. The concentrations of CO and UHC at the hallway exit were reduced by 51 percent and 94 percent, respectively, of the hallway entrance concentrations.

Case C. 20 cm inlet and 0 cm exit hallway soffits (20/0)

Two types of external burning were seen when a 20 cm inlet soffit was present in the hallway. The first type, graphically shown in Figure 10,

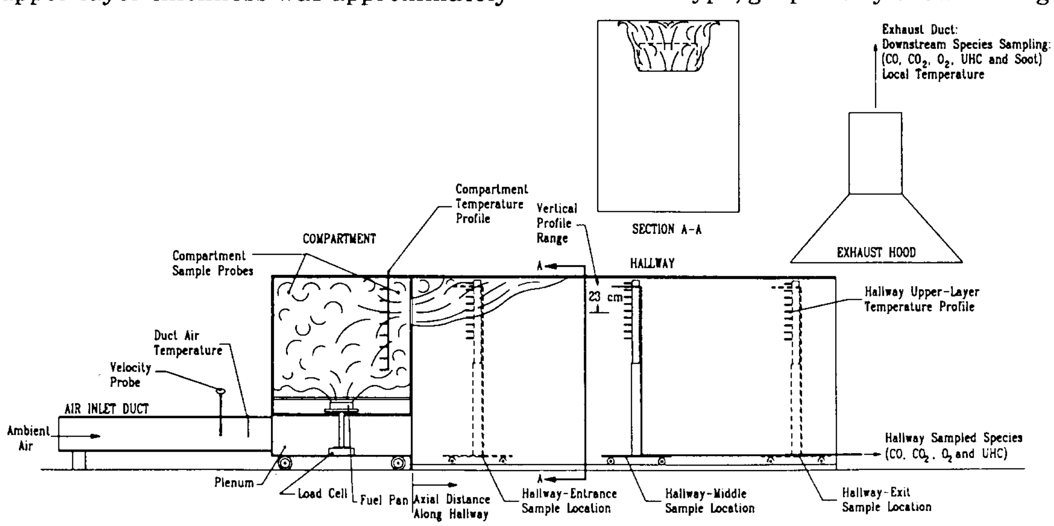

Figure 10. The buoyant-jet external burning which was sometimes present within a hallway having soffit geometries of (20/0) or (20/20).

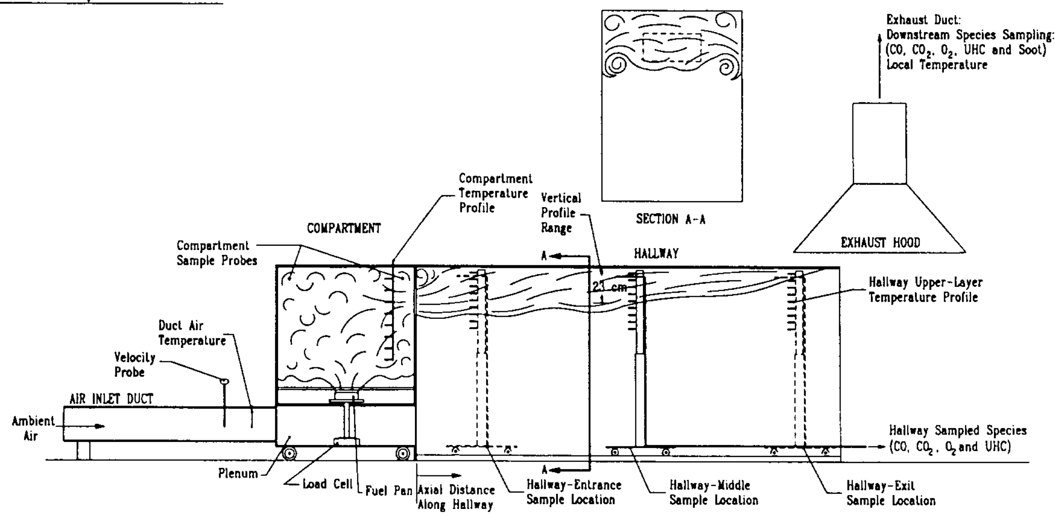

Figure 11. The buoyant, ceiling-jet external burning which was sometimes present within a hallway having soffit geometries of (20/0) or (20/20).

exhibited a burning buoyant jet which extinguished upon impinging on the hallway ceiling or shortly thereafter. Small vortical structures, as shown in Section A-A of Figure 10, were formed just after the flame impinged on the ceiling. In the second situation shown in Figure 11, the buoyant-jet from the compartment impinged upon the hallway ceiling and then traveled down the hallway as a ceiling-jet. For this type of burning, vortical structures were seen along the corners of the ceiling and the side walls. These structures were not as developed as those seen in the previous two soffit combinations. The first type of burning, termed confined buoyant-jet, was generally present with the smaller fire sizes and exhaust vent areas. The second type of burning, termed confined buoyant ceiling-jet, was generally present with the larger fire sizes and exhaust vent areas.

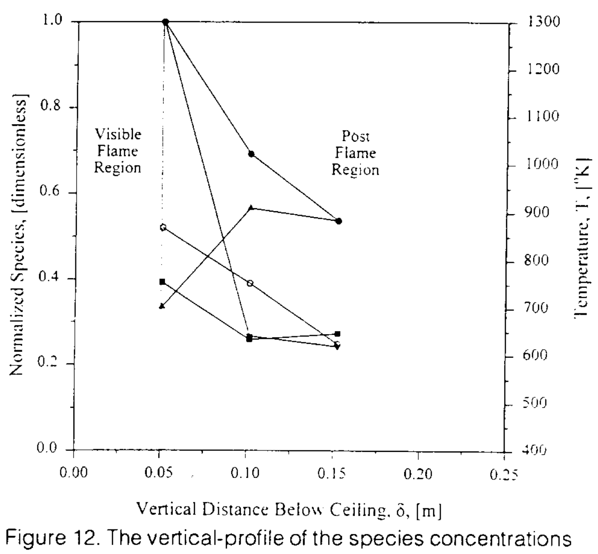

Figure 12. The vertical-profile of the species concentrations within the upper-layer in a hallway having a soffit geometry of (20/0). The average equivalence ratio was 1.54 and the average fire size was 367 kW. The graph notation and normalizing values are as follows: ●-CO(0.11%), ▼-UHC (0.074%), ■-CO_2(20%), ▲-O_2(21%) and O-Temperature.

The vertical-profile, shown in Figure 12, of the upper-layer exhaust gases 1.83 m down the hallway from the compartment was produced from experiments with a 1200 cm^2 exhaust vent area and a 20 cm diameter fuel pan. The external burning present in the hallway was a confined buoyant-jet, as seen in Figure 10. These fires had an average fire size of 367 kW and an average equivalence ratio of 1.54. By the time the exhaust gases had traveled half the length of the hallway, where the sampling cart was located, the fuel rich gas region (usually present between the ceiling and the visible flame region), had been oxidized. From the visual record of the tests, the visible flame region was extinguishing just as it reached the sampling cart, making $\delta_{U\text{-}L}\approx 5$ cm at most. The low temperatures, the high O_2 concentrations and low concentrations of CO and UHC at this location in the hallway were the result of efficient oxidation of the exhaust gases in the first half of the corridor. With the same exhaust vent area but a fire size of approximately 590 kW, the external burning changed to a confined buoyant, ceiling jet as seen in Figure 11. For this case, the upper layer thickness half way down the hallway increased to $\delta_{U\text{-}L}\approx$5-10 cm with all three upper layer regions present.

For experiments with a 1200 cm^2 exhaust vent area and a 20 cm diameter fuel pan, the axial variation in the exhaust gas levels along the hallway is shown in Figure 13a. The fires had an average equivalence ratio of 1.58 and an average fire size of 389 kW. The profile in Figure 13a was not refined enough to determine the location where the flame actually extinguished within the first half of the hallway. From the videotapes, the flame length was seen to be approximately 0.90 m down the hallway. As seen in Figure 13a, the toxic exhaust gases were nearly completely oxidized in the first half of the hallway. The concentrations of CO and UHC at the hallway exit were reduced by 96 percent and 99 percent, respectively, of the hallway entrance concentrations. This increase in reduction of the concentrations of CO and UHC was a result of the buoyant plume present in the first 0.90 m of the hallway. Alpert[17] and Hinkley *et.al.*[8] showed that a buoyant plume entrains air more efficiently than a ceiling jet. This was partially due to the buoyant plume being in a thermally unstable environment. The buoyant plume also had a larger surface area exposed to air compared to the ceilingjet. In experiments with the same exhaust vent area of 1200 cm^2 but a fire size of 575 kW and an equivalence ratio of 2.78, the exhaust gases formed a confined buoyant, ceiling-jet of external burning within the hallway. These exhaust gases varied along the length of the hallway, as shown in Figure 13b. The flame length for this situation was close to the length of the hallway, approximately 3.6 m. The oxidation of the CO and UHC was more efficient than that seen in the (0/0) and (0/20) cases, but less efficient than what was seen in the (20/0) soffit geometry for a small size fire. The oxidation is not as efficient as that seen in the Figure 13a because the gases entering the hallway are richer and require the entrainment of more air to oxidize them as effectively. This resulted in concentrations of CO and UHC being reduced by 80 percent and 94 percent, respectively, from the entrance to the exit of the corridor.

Case D. 20 cm inlet and 20 cm exit hallway soffits (20/20)

Similar to the (20/0) soffit case, this soffit case displayed the two different types of external burning which are shown in Figures 10 and 11. The vortical structures formed were similar to those seen in the (20/0) soffit combination.

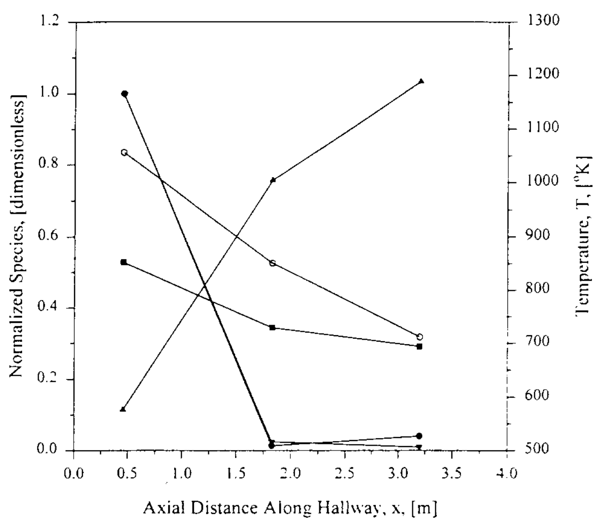

Figure 13a. The axial-profile of the species concentrations within the upper-layer in a hallway having a soffit geometry of (20/0). The average equivalence ratio was 1.58 and the average fire size was 389 kW. The graph notation and normalizing values are as follows: ●-CO(1.27%), ▼-UHC (1.01%), ■-CO_2(20%), ▲-O_2(10.5%) and O-Temperature.

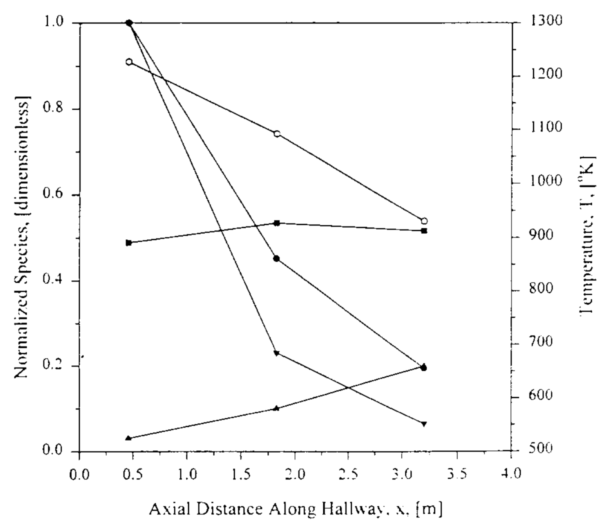

Figure 13b. The axial-profile of the species concentrations within the upper-layer in a hallway having a soffit geometry of (20/0). The average equivalence ratio was 2.78 and the average fire size was 575 kW. The graph notation and normalizing values are as follows: ●-CO (2.56%), ▼-UHC (4.36%), ■-CO_2(20%), ▲-O_2(10.5%) and O-Temperature.

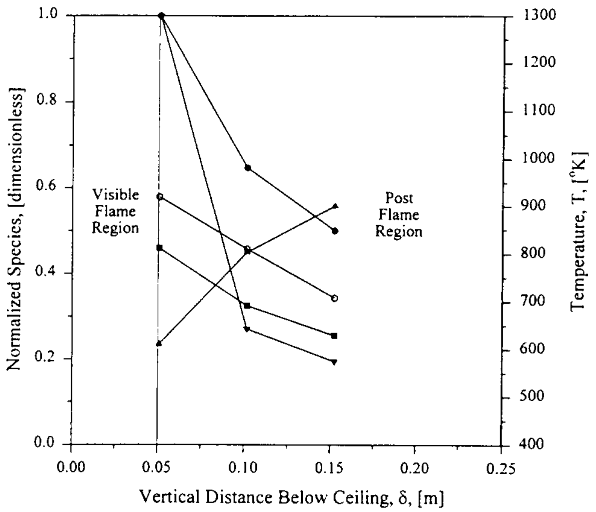

Figure 14. The vertical-profile of the species concentrations within the upper-layer in a hallway having a soffit geometry of (20/20). The average equivalence ratio was 1.74 and the average fire size was 380 kW. The graph notation and normalizing values are as follows: ●-CO(0.13%),▼-UHC (0.083%), ■-CO_2(20%), ▲-O_2(21%) and O-Temperature.

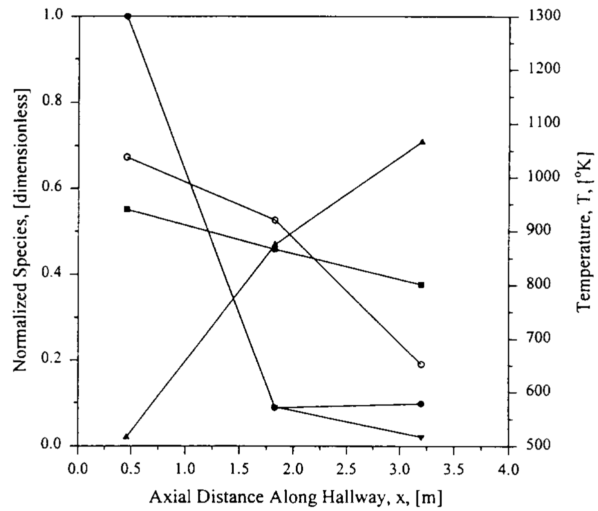

Figure 15. The axial-profile of the species concentrations within the upper-layer in a hallway having a soffit geometry of (20/20). The average equivalence ratio was 1.72 and the average fire size was 397 kW. The graph notation and normalizing values are as follows: ●-CO(1.43%), ▼-UHC (0.91%), ■-CO_2(20%), ▲-O_2(10.5%) and O- Temperature.

Experiments having a 1200 cm^2 exhaust vent area and a 20 cm diameter fuel pan contain an upper-layer 1.83 m from the compartment whose vertical profiles of species and temperature can be seen in Figure 14. The fires had an average size fire of 380 kW with an equivalence ratio of 1.74. The external burning took the form of a buoyant, ceiling-jet, as seen in Figure 11. The vertical-profile of the gases 1.83 m away from the compartment was nearly the same thickness, $\delta_{U\text{-}L} \approx$ 0-5 cm, as that seen in the smaller size fire with a (20/0) soffit geometry hallway (see Figure 12). In experiments with the same vent area but a fire size of 583 kW and an equivalence ratio of 2.56, all three regions of gases were present near the ceiling with an upper-layer thickness of $\delta_{U\text{-}L} \approx$5-10 cm. The concentrations of CO and UHC within the upper-layer were higher than those seen in the smaller size fire due to the higher equivalence ratio.

The axial-profiles of species and temperatures within the hallway for experiments conducted with a 1200 cm^2 exhaust vent area and a 20 cm diameter fuel pan are shown in Figure 15. The average equivalence ratio of the experiments was 1.72 while the average fire size was 397 kW. The external burning present in the hallway was a buoyant, ceiling-jet. From the temperature profile in Figure 15, the flame length within the hallway was expected to be close to 2.0 m. According to the visual records, the flame extinguished at approximately 1.8 m down the hallway, which was slightly longer than the case without an exit soffit. The concentrations of CO and UHC at the exit of the hallway were reduced by 90 percent and 98 percent, respectively, of the concentrations at the entrance of the corridor. The oxidation of the exhaust gases was not as efficient as the (20/0) case with a similar equivalence ratio and fire size (see Figure 13a), but the oxidation was still much better than the (0/0) and (0/20) soffit geometries (see Figures 7 and 9).

Flame Length

The flame length is often used to correlate phenomena in fires. Hinkley *et.al.*[8] correlated the flame length with the entrainment of air into the ceiling-jet contained within a hallway. The flame length in those experiments was solely related to the size of the fire in a fixed width hallway. In addition to the hallway width and the fire size, the flame length in the hallway of the present work also depended on the hallway soffit geometry within the corridor. The visual records of the experiments were used to estimate the flame length in the hallway.

For the (0/0) and (0/20) hallway soffit geometries, the flame length, l, which was normalized with the hallway length, l_0, varied according to the fire size, as seen in Figure 16.

The flame length when a buoyant jet was present in the hallway, (20/0) and (20/20) cases, was difficult to determine with a large amount of accuracy. With a buoyant, ceiling jet burning in the hallway, the normalized flame lengths were 0.85 for a 400 kW fire and 0.90 for a 550 kW fire. These are similar to values seen in Figure 16.

As expected, the flame length does correlate with the fire size for a particular inlet soffit height. A more precise measurement of the flame length will be performed in the future to investigate this correlation.

Correlations for Post-Hallway Species Yields

Many authors, including Beyler[9], Toner *et.al.*[10], Morehart *et.al.*[11], Gottuk *et.al.*[5,12,15] and Pitts[14], have correlated the CO yield inside a two-layer fire environment with the global equivalence ratio, defined by Equation 1. Gottuk[12] used the global equivalence ratio to predict the CO yield in the exhaust gases collected in a hood as they exited the compartment. From Figures 3 and 4, it was seen that the global equivalence ratio does not, unfortunately, accurately predict the species yields downstream of the corridor which was located adjacent to the burning compartment. The oxidation of the exhaust gases within the hallway was found to be sensitive to the fluid mechanics within the hallway. A dimensional analysis was performed on the variables most relevant to the oxidation of exhaust gases within the hallway. The non-dimensional groups generated from this dimensional analysis were used to develop correlations to predict the CO and UHC yields downstream of the hallway.

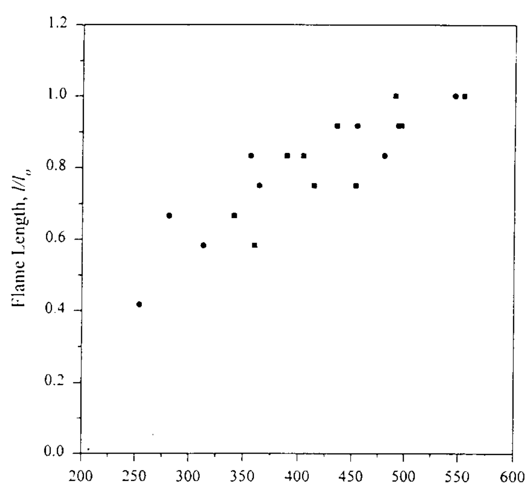

Figure 16 The flame length, normalized with the hallway length of l_o=3.66 m. for hallways having a (0/0) soffit geometry and a (0/20) soffit geometry. The graph notation is as follows: ●-(0/0) soffit geometry and ■-(0/20) soffit geometry.

The mass flow rate of CO within the exhaust duct is a function of

$$\dot{m}_{CO} = f(\dot{m}_{vent}, A_{vent}, P_{vent}, Q, h_{in}, h_{exit}, \rho_{vent}, \rho_{air}, \phi), \quad (6)$$

i.e,. nine different variables. The mass flow rate of UHC within the exhaust duct is a function of the same nine variables so the nondimensional groups obtained from the CO dimensional analysis will also be used to predict the UHC yield.

There are ten variables containing three basic dimensions, so the dimensional analysis should result in no more than seven different dimensionless groups. The repeated variables used in the dimensional analysis were chosen to be $\dot{m}_{vent}$, ρ_{vent} and A_{vent}. The nondimensional groups obtained were:

$$\pi_1 = \frac{\dot{m}_{CO}}{\dot{m}_{vent}} \quad \pi_2 = \frac{P_{vent}}{\sqrt{A_{vent}}} \quad \pi_3 = \frac{h_{in}}{\sqrt{A_{vent}}} \quad \pi_4 = \frac{h_{exit}}{\sqrt{A_{vent}}}$$

$$\pi_5 = \frac{QA^2{}_{vent}P^2{}_{vent}}{\dot{m}^3{}_{vent}} \quad \pi_6 = \frac{P_{air}}{\rho_{vent}} \quad \pi_7 = \phi$$

Defining the CO yield as π_1, it can be said that the CO yield

$$Y_{CO} = \frac{\dot{m}_{CO}}{\dot{m}_{CO}} = F\left(\frac{P_{vent}}{\sqrt{A_{vent}}}, \frac{h_{in}}{\sqrt{A_{vent}}}, \frac{h_{exit}}{\sqrt{A_{vent}}}, \frac{QA^2{}_{vent}P^2{}_{vent}}{\dot{m}^3{}_{vent}}\right) = F(\Psi) \quad (7)$$

is a function of the remaining dimensionless groups. Similarly, the yield of UHC

$$Y_{UHC} = \frac{\dot{m}_{UHC}}{\dot{m}_{UHC}} = F\left(\frac{P_{vent}}{\sqrt{A_{vent}}}, \frac{h_{in}}{\sqrt{A_{vent}}}, \frac{h_{exit}}{\sqrt{A_{vent}}}, \frac{QA^2{}_{vent}P^2{}_{vent}}{\dot{m}^3{}_{vent}}\right) = F(\Psi) \quad (8)$$

also be said to be functions of these dimensionless groups. Nondimensional group six was omitted since the density of the air at the exhaust gas-air interface was not measured.

The CO yield was found to correlate with a function

$$Y_{CO} = F\left(\frac{QA^2_{vent}\rho^2_{vent}}{\dot{m}^3_{vent}} \frac{P_{vent}}{\sqrt{A_{vent}}} e^{-C_1} 1.1^{C_2} \phi\right) = F(\Psi) \quad (9)$$

which included all of the pi groups given in Equation 7. Similarly, the yield UHC

$$Y_{UHC} = F\left(\frac{QA^2_{vent}\rho^2_{vent}}{\dot{m}^3_{vent}} \frac{P_{vent}}{\sqrt{A_{vent}}} e^{-C_1} 1.1^{C_2} \phi\right) = F(\Psi) \quad (10)$$

where;

$$C_1 = \frac{h_{in}}{\sqrt{A_{vent}}} \qquad C_2 = \frac{h_{exit}}{\sqrt{A_{vent}}}$$

can be correlated to this same function. Figure 17 shows a plot of the CO yield, as defined by Equation 7, plotted against the function shown in Equation 9. The UHC yield, as defined in Equation 8, is also plotted versus this function and is shown in Figure 18. A curve fit was applied to the data points and yielded the following expressions to predict the downstream yield of CO and UHC.

$$Y_{CO} = (0.026/155)\tan^{-1}\left(\frac{(\Psi - 5647)}{2730}\right) + (0.012) \quad (11)$$

$$Y_{UHC} = (0.010/167)\tan^{-1}\left(\frac{(\Psi - 7146)}{2134}\right) + (0.059) \quad (12)$$

From the plots, it is seen that the oxidation of CO was more sensitive to the exhaust gas fluid mechanics within the hallway compared with the UHC oxidation within the hallway.

Since these results are from a reduced scale facility, scaling laws may be necessary to apply the results to an actual building fire situation. However, no attempt has been made in this study to develop scaling laws for the oxidation of CO and UHC within a corridor adjacent to a burning compartment.

Summary and Conclusions

In order to be able to predict the amount of toxic exhaust gases being transported from an underventilated room fire to a remote location in a building, a thorough understanding of the transport and oxidation of the exhaust gases is necessary. In the investigation reported here, the evolution of compartment fire exhaust gases in an attached hallway was experimentally studied. The fluid mechanics of the exhaust gases within the hallway were varied by changing the soffit heights at either end of the hallway, the size of the fire within the compart-

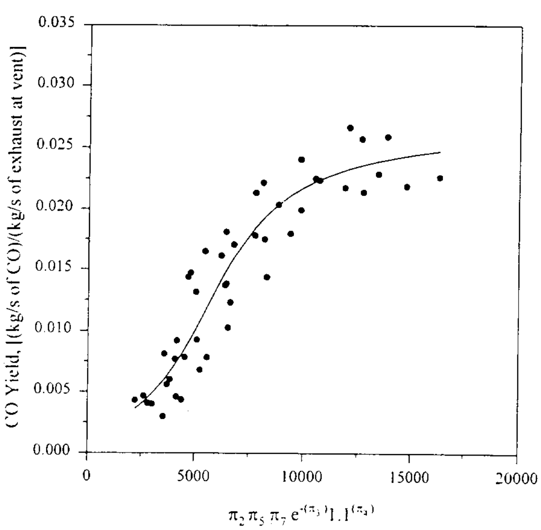

Figure 17. The CO yield downstream of the hallway plotted against the dimensionless function defined in Equation 9. The curve fit of the points is described by Equation 11.

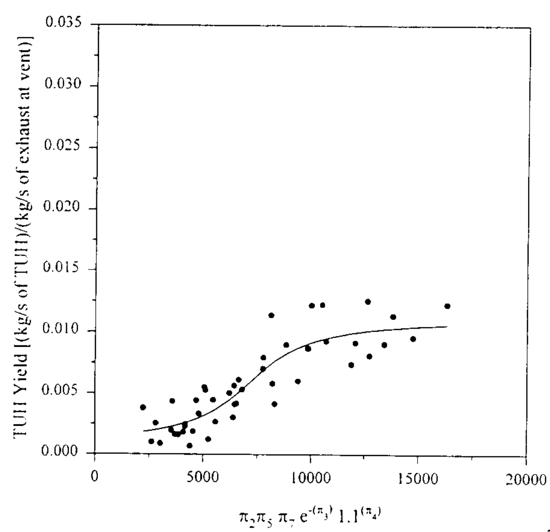

Figure 18. The UHC yield downstream of the hallway plotted against the dimensionless function defined in Equation 10. The curve fit of the points is described by Equation 12.

ment and the window-style exhaust vent area which connects the compartment to the hallway. Each of these variables was found to have an effect on the oxidation of the exhaust gases.

The presence of a 20 cm soffit at the entrance of the hallway was found to dramatically increase the rate of oxidation of the exhaust gases due to the presence of a buoyant plume at the entrance of the corridor. The buoyant plume resulted in an increase in the air entrainment into the upper-layer gases. The effect of the addition of a soffit at the exit of the hallway depended on the upstream geometry. The oxidation of the exhaust gases was impeded when there was no soffit at the entrance of the hallway for all fire sizes investigated and when there was a 20 cm soffit at the hallway entrance with a larger size fire (greater than approximately 400 kW) inside the compartment. The impedance of the exhaust gas oxidation was due to a thickening of the upper-layer within the corridor. The oxidation of the exhaust gases was unaffected by the presence of an exit soffit when there was a 20 cm soffit at the entrance of the hallway with a smaller size fire (less than approximately 400 kW) within the compartment. In the latter case, the effective oxidation of CO and UHC within the first half of the corridor caused the addition of a soffit at the hallway exit to have only a small effect on the concentration levels of CO and UHC leaving the hallway.

The fire size and the exhaust vent area also affected the levels of toxic gases within and downstream of the hallway. A larger size fire for a given soffit combination and exhaust vent area produced larger amounts of toxic gases usually resulting in an increase in the amount of toxic gases which escaped the hallway not oxidized. As the exhaust vent area was reduced for a given soffit combination and fire size, the oxidation of the exhaust gases was increased.

The entrainment of air into the upper layer of the hallway was found to have both a positive and negative effect on the oxidation of the exhaust gases. Obviously, it is desirable to entrain enough air into the upper-layer so that all of the exhaust gases can be oxidized. The air that is entrained, though, cools the upper layer gases and eventually "freezes out" the oxidation reactions before all of the exhaust gases can be oxidized. When the external burning is a ceiling-jet or a buoyant, ceiling-jet, the entrained air cools the exhaust gases before they can be fully oxidized. When the external burning is a buoyant-jet, the air entrainment is efficient enough that the exhaust gases can be reduced significantly.

Nondimensional parameters relevant to the oxidation of the compartment fire combustion gases which are exhausted into an adjacent corridor were developed. The analysis took into consideration the hydrodynamics of the exhaust gases at the hallway entrance, including the exhaust vent area and hallway soffit geometries, and the fire size as an ignition source for the hallway gases. The nondimensional groups formed from this analysis were used to develop correlations which predict the CO and UHC yields (based on the mass flow at the exhaust vent instead of the fuel vaporization rate) downstream of the compartment. The non-dimensional correlations reaffirm the results of the measurements indicating that the oxidation of CO is more sensitive to the variation in the fluid mechanical effects and the fire size than the oxidation of UHC.

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NOMENCLATURE

A	area, (m^2)
h	soffit height, (m)
l	flame length, (m)
lo	hallway length, (m)
$\dot{m}$	mass flow rate, (kg/s)
MW	molecular weight, (kg/kmol)
$\dot{n}$	molar flow rate, (kmol/s)
P	perimeter of buoyant plume at hallway entrance, (m)
Q	fire size, (kW)
X	mole fraction
Y	yield

Greek Symbols

δ	region thickness in hallway upper-layer, (cm)
η	efficiency, (%)
ϕ	equivalence ratio
ρ	density, (kg/m^3)

Subscripts

air	ambient air
C,i	compartment species
CO	carbon monoxide
exh	exhaust duct
exit	hallway exit
E,i	exhaust duct species
fuel	fuel vaporization
FRR	fuel rich region
i	species
in	hallway inlet
i, wet	wet species
oxid	oxidation
p	plume
st	stochiometric
UHC	total unburned hydrocarbons
U-L	upper-layer
vent	exhaust vent
VFR	visible flame region